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# The explosion of supernova 2011fe in the frame of the core-degenerate scenario

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## ABSTRACT

We argue that the properties of the Type Ia supernova (SN Ia) SN 2011fe can be best explained within the frame of the core-degenerate (CD) scenario. In the CD scenario, a white dwarf (WD) merges with the core of an asymptotic giant branch (AGB) star and forms a rapidly rotating WD, with a mass close to and above the critical mass for explosion. Rapid rotation prevents immediate collapse and/or explosion. Spinning down over a time of $0{-}10^{10}$ yr brings the WD to explosion. A very long delayed explosion to post-crystallization phase, which lasts for about $2 \times 10^9$ yr, leads to the formation of a highly carbon-enriched outer layer. This can account for the carbon-rich composition of the fastest-moving ejecta of SN 2011fe. In reaching the conclusion that the CD scenario best explains the observed properties of SN 2011fe, we consider both its specific properties, like a very compact exploding object and carbon-rich composition of the fastest-moving ejecta, and the general properties of SNe Ia.

**Key words:** supernovae: general – supernovae: individual: SN 2011fe.



## 1 INTRODUCTION

SN 2011fe is a typical Type Ia supernova (SN Ia). It was discovered by Nugent et al. (2011), and there is a wealth of observations that constrain its properties. These constraints can be summarized as follows (Chomiuk 2013). (1) The exploding object had a radius of $R_* \lesssim 0.02\,\mathrm{R}_\odot$ (Bloom et al. 2012), although other less severe constraints are discussed elsewhere, e.g. Mazzali et al. (2013) who give $R_* \lesssim 0.06\,\mathrm{R}_\odot$, and Piro & Nakar (2012). (2) The fastest-moving ejecta at $v > 19\,400\,\mathrm{km\,s^{-1}}$ are almost exclusively (98 per cent by mass) composed of carbon (Mazzali et al. 2013). (3) The explosion was mildly asymmetric (Smith et al. 2011b). (4) There are no indications for circumstellar material (CSM). (5) Very strong constraints on the properties of a possible companion have been placed (Li et al. 2011). Actually, it seems as if the progenitor of SN 2011fe was all alone when it exploded: no binary companion, no material around it, no violent event much before explosion and no CSM. Observations of course only put limits on some physical parameters, but these are so strong that they strongly challenge the double-degenerate (DD) scenario and basically rule out the most popular single-degenerate (SD) scenarios for SN 2011fe. There is one speculative SD channel that can better explain SN 2011fe, which we discuss below.

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In this Letter, we show that these properties can be best explained within the frame of the core-degenerate (CD) scenario. The plan of this Letter is the following. In Section 2, we confront with observations four basic theoretical scenarios for the formation of the progenitor of SN 2011fe. (i) First is the SD scenario (e.g. Whelan & Iben 1973; Nomoto 1982; Han & Podsiadlowski 2004) where a white dwarf (WD) grows in mass through accretion from a non-degenerate stellar companion. Ruiter et al. (2011) consider the helium-rich donor scenario (Iben et al. 1987) to be a separate category from the canonical SD scenario. We refer to accretion of helium-rich material under the double-detonation (DDet) category. (ii) Second is the DD scenario (Webbink 1984; Iben & Tutukov 1984), where two WDs merge after losing angular momentum and energy through the radiation of gravitational waves (Tutukov & Yungelson 1979). There are suggestions that sub-Chandrasekhar-mass remnants can also lead to explosions (e.g. van Kerkwijk, Chang & Justham 2010; Badenes & Maoz 2012). (iii) Third is the DDet mechanism where a sub-Chandrasekhar-mass WD accumulates a layer of helium-rich material on the surface, which under the right conditions can detonate (Shen, Guillochon & Foley 2013, and references therein). (iv) Fourth is the CD scenario where a Chandrasekhar- or super-Chandrasekhar-mass WD is formed at the termination of the common envelope (CE) phase or during the planetary nebula phase, from a merger of a WD companion with the hot core of a massive asymptotic giant branch (AGB) star (Livio & Riess 2003; Kashi & Soker 2011; Ilkov & Soker 2012, 2013;

Soker et al. 2013; Tsebrenko & Soker 2013). There is some overlap between these scenarios. For example, a violent merger route of the DD scenario can end up in DDet (Pakmor et al. 2013). In Section 3, we discuss how the fastest ejecta of SN 2011fe can be enriched in carbon, as a consequence of carbon–oxygen phase separation upon crystallization. A short summary is given in Section 4.

## 2 THE PROPERTIES OF SN 2011fe

Chomiuk (2013) presents a general summary of the properties of SN 2011fe and the way they constrain the SD and DD scenarios. Here, we limit the discussion to some specific properties that hold the key to rank the likelihood of the different scenarios. We also briefly discuss the strong and weak points of each scenario in relation to general properties of SN Ia. Moreover, since PTF 11kx is frequently mentioned as being the result of an SD event, we would like to express here our stand that this cannot be the case, because the massive CSM of PTF 11kx can be much better explained by the CD scenario (Soker et al. 2013).

As SN 2011fe appears to be a normal SN Ia, we consider only those scenarios that are claimed to account for a large fraction of SNe Ia. The WD–WD collision model (Katz & Dong 2012; Kushnir et al. 2013) can account for at most few per cent of all SNe Ia (Hamers et al. 2013; Prodan, Murray & Thompson 2013), and is not discussed here. One can reach this conclusion by considering the different demands on this process. These include a small fraction of triple systems (Leigh & Geller 2013), the requirement that progenitors of SN Ia have $M \lesssim 1.7\,\mathrm{M}_{\odot}$ to be compatible with the delay-time distribution (DTD; Greggio, Renzini & Daddi 2008), and the limitation that merger cannot take place before the formation of two WDs (Hamers et al. 2013).

We now turn to discuss some specific items of the scenarios. Most awkward to the SD scenario is that no companions are found in nearby supernovae remnants of SN Ia. This holds for SN 2011fe as well. The second general weak point of the SD scenario is that it can account neither for the shape of the DTD nor for the total number of SN Ia (e.g. Nelemans, Toonen & Bours 2013). The strongest prediction of the SD scenario is the presence of hydrogen in the CSM. However, when a hydrogen-rich CSM is detected it is too massive to be accounted for by the SD scenario, as for PTF 11kx (Soker et al. 2013). One way to overcome some of the problems of the SD scenario is to assume that rotation of the WD delays the explosion till long after accretion ceases (Di Stefano, Voss & Claeys 2011; Justham 2011). This delay has some common properties with the delay of the CD scenario, and can explain some properties of SN 2011fe much as the CD scenario does. However, this does not solve other problems of the SD scenario, such as that it is expected to explain only a small fraction of SNe Ia, and that it is not clear that the WD can grow by accretion to the Chandrasekhar mass limit.

The strongest character of the DD scenario is that it well explains the DTD (e.g. Maoz & Mannucci 2012; Nelemans et al. 2013; Ruiter et al. 2013). However, the ignition process and whether sub-Chandrasekhar systems can explode are still open questions. Mergers of two WDs might release large amounts of gravitational energy in the form of electromagnetic radiation. If the WD–WD merger occurs much before the explosion, we would expect to see many transient events with luminosity not much below, and even higher, than in SN Ia. These are not observed. This and other considerations led to the study of prompt ignition mechanisms, such as the violent merger scenario (Pakmor et al. 2011, 2012, 2013) that was confronted with SN 2011fe by Röpke et al. (2012). Violent mergers lead to highly asymmetrical explosions (Pakmor et al. 2011, 2012, 2013), with a large departure from axisymmetry. Smith et al. (2011b) conducted a spectropolarimetry study of SN 2011fe and concluded that '[the small polarization] is suggestive that there is some small amount of global asymmetry in the ejecta of SN 2011fe, perhaps even suggesting axial symmetry in the event.' This is compatible with the finding that well-resolved close-by SN Ia remnants are close to being spherical (Lopez et al. 2011). The close to spherical morphologies pose a strong challenge to the violent merger ignition mechanism.

In the studies of Pakmor et al. (2011, 2012), carbon is ignited on the accreting WD. This can reduce the carbon abundance in the fastest moving gas, as in the violent merger model for subluminous SN Ia studied by Pakmor et al. (2011). This is contrary to the observations of SN 2011fe that has 98 per cent carbon-rich material in the fastest-moving ejecta (Mazzali et al. 2013). The carbon-rich fastest ejecta are also problematic for models based on helium accretion, such as the DDet scenario (Mazzali et al. 2013). Instead, Mazzali et al. (2013) prefer accretion of hydrogen that is burned to carbon during the explosion. In the CD scenario, the long time that laps between the core–WD merger and the explosion allows carbon to separate from oxygen when the WD crystallizes. We elaborate on this in Section 3.

In the violent merger process, only part of the mass lost by the destructed WD is accreted on to the more compact WD. The rest of the mass expands up to a distance of about 0.03–0.04 $\mathrm{R}_{\odot}$ from the exploding WD (Pakmor et al. 2011, 2012, 2013). In the simulations of Pakmor et al. (2012), the shock breaks out of the gas at a radius of about 0.04–0.05 $\mathrm{R}_{\odot}$. This is on the edge of what can be compatible with the limits on the size of the exploding WD in SN 2011fe. The actual limits on the violent merger process and on any Roche lobe overflow (RLOF) process by the size of the exploding WD of SN 2011fe are even more tight. The reason is that the mass transfer proceeds via an accretion disc lasting for at least several tens of orbital periods, greater than about 100 s. It is very likely that a disc-wind and/or jets are blown during this period with velocities close to the escape velocity from the accreting WD, about 5000 km s$^{-1}$ (Ji et al. 2013). Therefore, outflowing gas perpendicular to the equatorial plane will reside at distances of about 1 $\mathrm{R}_{\odot}$ at the time of explosion.

The DDet scenario has been thoroughly discussed in recent years (e.g. Sim et al. 2012; Shen et al. 2013), as it can well account for ignition, as well as for other properties of SN Ia (e.g. Ruiter et al. 2011). The helium can be supplied from a degenerate or a non-degenerate companion. Observational constraints on the DDet depend on the nature of the mass donor star. If it is non-degenerate (degenerate) then some of the drawbacks of the SD scenario (DD scenario) are applicable. In addition, for the specific case of SN 2011fe the carbon-rich fastest ejecta are difficult to explain with helium accretion (Mazzali et al. 2013).

The conclusion of this discussion is that there is no scenario exempt of problems. As for the specific case of SN 2011fe, it seems that the CD scenario does the best. The most puzzling observation that the fastest ejecta are 98 per cent rich carbon is dealt with in the next section.

## 3 THE CARBON-RICH FAST EJECTA

As previously discussed, none of the standard scenarios is able to satisfactorily account for the presence of an almost pure carbon shell in the fastest, outermost region of the ejecta. The CD scenario, however, is able to explain this feature. It is expected that in the merger of an AGB star and a WD, the tiny H envelope (about

$10^{-4}$ M$_\odot$) and He buffer (about $10^{-2}$ M$_\odot$) are ejected or burned as a consequence of the dynamical interaction (Dan et al. 2013). Thus, we foresee that the result of such interaction is a WD with a bare carbon–oxygen core. Actually, there is observational evidence for WDs devoid of these external H- and He-rich layers (Gänsicke et al. 2010). Moreover, SPH simulations (Lorén-Aguilar, Isern & García-Berro 2009) show that the resulting WD has a rapidly rotating and hot convective corona, which is prone to the magnetorotational instability (García-Berro et al. 2012; on the MRI see Balbus & Hawley 1991). Consequently, the remnant of the merger should be a rapidly rotating, magnetized WD. The outer hydrogen and helium layers of the core and WD will actually carry the extra angular momentum and be expelled from the merged product. If the delay time is sufficiently long, as we propose for SN 2011fe, the ejecta of the merger has long gone and the WD goes through crystallization. In passing, we note that in the SD and DDet scenarios, accretion from a non-degenerate companion keeps the core warm and prevents crystallization. During the crystallization phase the concentrations of carbon and oxygen are not the same in the liquid and the solid phase (García-Berro et al. 1988; García-Berro et al. 2010). The oxygen abundance is higher in the solid phase. Hence, the denser oxygen-rich solid sinks and the carbon-rich liquid is homogeneized by Rayleigh–Taylor instabilities (Isern et al. 1997, 2000). The result of this process is that, as crystallization proceeds, the outer layers of the WD become richer in carbon.

To check whether or not this is a viable scenario to explain the enhanced carbon abundance of the very outer layers of SN 2011fe, we followed the evolution of the bare core of a 1.38 M$_\odot$ WD from the knee in the Hertzsprung–Russell (HR) diagram until the luminosity of the WD was as low as $\log(L/\mathrm{L}_\odot) \simeq -5.0$ (see Althaus et al. 2010 for details). The knee in the HR diagram is the phase when the luminosity and temperature of the young WD start to decrease. We considered that the WD had no He nor H outer layers since, as mentioned, these layers are very likely ejected during the merger. The results are shown in Figs 1 and 2. The core is

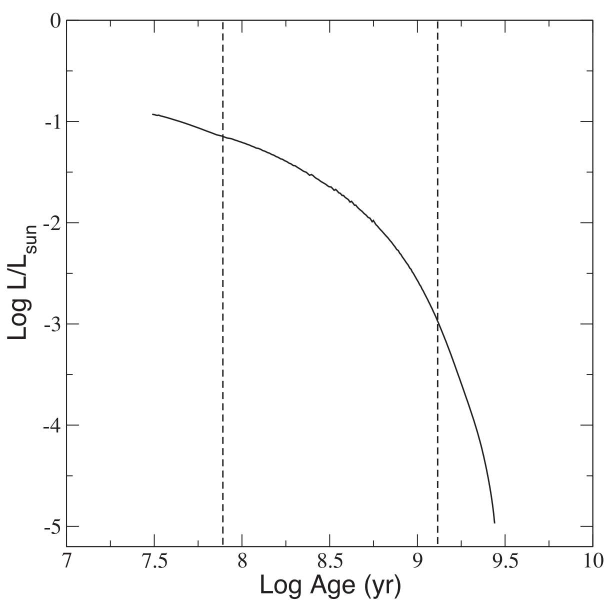


**Figure 1.** Cooling sequence of the bare nucleus of a 1.38 M$_\odot$ carbon–oxygen WD. The leftmost dashed vertical line shows when crystallization starts at the centre of the star, while the rightmost marks when the core is 95 per cent crystallized.

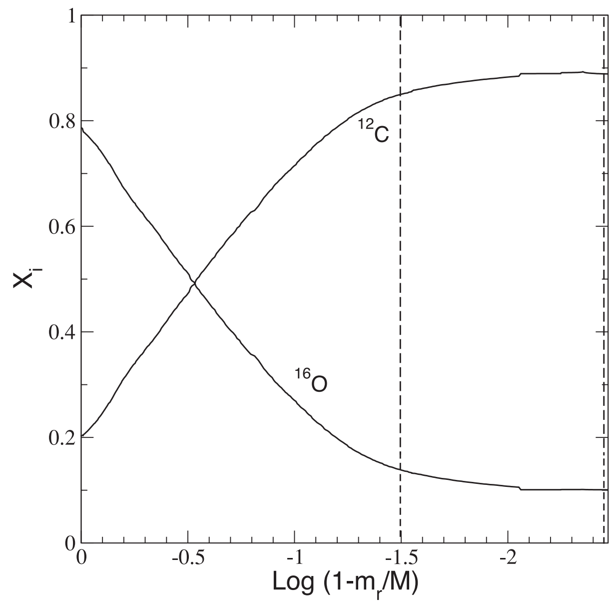


**Figure 2.** Chemical profile of the WD of Fig. 1 when the core is 95 per cent crystallized. Shown is the composition from the centre of the WD to $10^{-3}M$ from its surface as a function of $\log(1 - m_r/M)$. Here, $m_r$ is the mass inner to radius $r$ and $M$ is the total mass of the WD. The vertical dashed line shows the mass coordinate at which the carbon mass abundance is largely enhanced by crystallization ($X_\mathrm{C} \gtrsim 0.85$).

95 per cent crystallized at $t_\mathrm{cool} \simeq 1.4$ Gyr, a relatively short delay (Fig. 1). By that time the luminosity of the WD is $\log(L/\mathrm{L}_\odot) \simeq -3.1$, its effective temperature is $\log T_\mathrm{eff} \simeq 4.3$, and it has an outer layer of mass $\Delta M \approx 0.045$ M$_\odot$ where the carbon mass abundance is $X_\mathrm{C} \simeq 0.9$ (Fig. 2). For lower luminosities, the carbon abundance in the very outer layers does not change appreciably. Thus, we expect that, after a sufficiently long time, the explosion of such WD results in the very outer layers being largely enhanced in carbon, in good, but not perfect, agreement with the observations of SN 2011fe.

## 4 SUMMARY

SN 2011fe is an archetypical SN Ia that was observed shortly after it exploded. The early detection allowed us to strongly constrain the properties of its progenitor. Studies in the past two years confronted some theoretical models with these constraints. However, the CD scenario was not considered in any of these studies. Here, we argue that the CD scenario best accounts for the properties of SN 2011fe. Our arguments, which were discussed in Section 2, are compared to the most relevant properties of SN 2011fe, as collected by Chomiuk (2013), in Table 1. From our presentation of the observed and expected properties of SN 2011fe it is evident that no scenario is free of problems. However, it seems that the CD scenario best survives the different limits on the properties of the SN 2011fe progenitor.

Although the CD scenario does well with the constraints on the progenitor of SN 2011fe, some of the properties of the CD scenario are still poorly determined and deserve further study.

(i) Carbon enriched ejecta (Section 3). The post-crystallization model of WDs presented in Section 3 brings the carbon enrichment to about 90 per cent, a little short of the observed 98 per cent. We envisage two possibilities that can improve the agreement with observations, although we do not discard other effects. First, the derived abundances are based on the spectral fittings of SN 2011fe

**Table 1.** Confronting four SN Ia scenarios with the properties of SN 2011fe.

| | Single degenerate | Double degenerate | Double detonation | Core degenerate |
|---|---|---|---|---|
| SN 2011fe: $R_* < 0.02\,\mathrm{R}_\odot$[a] | Expected | Marginal for violent merger | Depends on donor type | Expected |
| SN 2011fe: 98 per cent carbon in fastest ejecta | Possible[b] | Not expected | Problematic[b] | Separation after crystallization |
| SN 2011fe: Mildly asymmetric explosion | Expected | Highly asymmetric explosion | Depends on mass transfer process | Expected |
| SN 2011fe: No circumstellar material | Magic is needed to hide companion and its wind | Expected | Depends on mass transfer process | Expected in most cases |
| SN 2011fe: Strong limits on a companion | | Expected | Depends on donor | Expected |
| General: Strong characteristics | Accreting massive WDs exist | Explains very well the delay time distribution (DTD) | Ignition easily achieved | Explains both SN Ia with H-CSM and symmetric explosion |
| General: Weak characteristics | (1) Cannot account for DTD; (2) companions not found | Ignition process (violent merger has too-asymmetric ejecta) | Same as for SD and DD, depending on type of donor | More work on (1) delay-parameter; (2) merger during CE; (3) find massive single WDs |
| PTF 11kx: Hydrogen-rich and massive CSM | CSM too massive | Not expected at all | CSM too massive | Expected in rare cases[c] |

*Notes.*
[a] $R_\star$ is the radius of the exploded star.
[b] Mazzali et al. (2013)
[c] Soker et al. (2013).

with the W7 model of Iwamoto et al. (1999) and an improved model (W7$^+$) specifically designed to obtain a better fit to the observed spectrum. These models have very different density profiles, such that a small change in the slope of the density profile of the ejecta may change the carbon abundance by a few per cent, bringing our results in better agreement with observations. Secondly, the carbon abundance in the very outer layers depends on the initial carbon abundance in the inner core, which depends on the $^{12}\mathrm{C}(\alpha,\,\gamma)^{16}\mathrm{O}$ reaction rate, as well as on the temperature and density profiles of the progenitor star. This reaction rate is still uncertain, and small changes in the cross-section may result in enhanced carbon abundance in the core (e.g. Salaris et al. 1997). Nevertheless, an in-depth study of these effects should be made in subsequent works.

(ii) The core-WD merger process. In this process, either the core or the WD is destroyed and accreted by the other object. When the accreting object approaches the Chandrasekhar limit it contracts and releases gravitational energy. We speculate that this regulates the final merged product to be of about the Chandrasekhar mass (Tornambé & Piersanti 2013), with some mass spreading due to rapid rotation.

(iii) The delay parameter. To account for the delay time distribution of $\mathrm{d}N_{\mathrm{Ia}}/\mathrm{d}t_{\mathrm{SF}} \propto t^{-1}$ (Maoz & Mannucci 2012), where $t_{\mathrm{SF}}$ is the time since star formation, a parameter to which the delay time is very sensitive is required. Namely, the time from star formation to explosion sensitively depends on some parameter $\aleph$, such that $\tau_{\mathrm{e}} \propto \aleph^{\eta}$ with $\eta \gg 1$. For the CD scenario, this can be the angular momentum loss (Ilkov & Soker 2012; Tornambé & Piersanti 2013) or the decay of the magnetic field, or another parameter. This will be studied in a future work.

(iv) The properties of the merged product should be determined in order to search for such massive WDs. Tout et al. (2008) considered a merger of a WD with a core of an AGB star to explain the formation of massive rotating WDs with strong magnetic fields, and Wickramasinghe & Ferrario (2000) commented that such WDs might be more likely to form SN Ia. WDs with strong magnetic fields and mass around the Chandrasekhar mass are predicted to exist by our scenario. However, their observational properties should be better determined. For example, whether the merger process removes all hydrogen and even helium.

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